(Super)rare decays of an extra Z' boson via Higgs boson emission

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Abstract

The phenomenological model of an extra U(1) neutral gauge Z' boson coupled to heavy quarks is presented. In particular, we discuss the probability for a light Z_2 mass eigenstate decay into a bound state composed of heavy quarks via Higgs boson emission.

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1. Theoretical interest in an extra neutral vector boson Z' is mainly motivated by experimental observation of possible deviations from the Standard Model (SM) predictions for the decay of the SM Z boson into $\bar{c}c$- and $\bar{b}b$- pairs of quarks (R_c- and R_b-ratios) [1]. The deviations may be considered as one of the indications of new physics (NP) beyond the SM. The promising explanation of the observed phenomena is implied in the extra Z' models (see refs. [7-16] in [2]). New gauge bosons can be detected in future high-energy colliders, namely, Large Hadron Collider (LHC) at CERN, which can test the nature and structure of many theoretical models at a scale of 1 TeV, at least. Theoretical predictions of new neutral or charged gauge bosons come from various extensions of the SM [3]. New extra bosons naturally appear in the Grand Unification Theory (GUT) models [3]. A simple and well-known version among the extensions of the SM is the minimal one, aimed at unifying interactions, the E_6 GUT model [3]. Since the breaking of E_6 GUT into SM is accompanied by at least one extra U(1) group

($E_6 \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)$), there may exist a heavy neutral boson Z' which can mix with an ordinary Z boson. There are two new gauge bosons appearing in E_6 GUT models [3] where only one originates from the SO(10) subgroup

$$E_6 \supset SO(10) \times U(1)_\Psi \ ,$$

$$SO(10) \supset SU(5) \times U(1)_\chi \ ,$$

$$SU(5) \supset SU(3)_C \times SU(2)_L \times U(1)_Y,$$

while the Z' boson is a composition of Z_Ψ- and Z_χ- components mixed with a free angle Θ [3]:

$$Z' = Z_\Psi \ cos\Theta - Z_\chi \ sin\Theta \ .$$

The best sensitivity to a possible signal from Z' is achieved through the decay channel, $Z' \to \bar{Q}Q$, where Q ($\bar{Q}$) stands for a heavy quark (antiquark). The decay $Z' \to \bar{Q}Q$ is the most important though not the only production signal possible for Z'. To search for Z' at LHC, it is important to know as much as possible about their decay modes in both the standard Drell-Yan (DY)- type sectors and the (super)rare ones. Other channels can provide important information on the Z' boson couplings. If we go beyond SM, there are several possibilities for some quark bound state resonances $B \equiv \{\bar{Q}Q\}$ to be produced via the particle interplay accompanied by the Higgs-boson (H) emission. A possible extension of the SM adopting a Z' boson may need more unknown h-fermions (spin-1/2 heavy exotic quarks) and H particles to be included. It is known that the Z boson is not yet an exact mass eigenstate, but turns out to be mixed with Z'. In the $Z - Z'$ mixing scheme the mass eigenstates Z_1 and Z_2 are rotated with respect to the basis Z and Z'

$$\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} \cos\kappa & \sin\kappa \\ -\sin\kappa & \cos\kappa \end{pmatrix} \begin{pmatrix} Z \\ Z' \end{pmatrix} \ ,$$

by the mixing angle κ

$$\kappa = \arctan\left(\frac{M_Z^2 - M_{Z_1}^2}{M_{Z_2}^2 - M_Z^2}\right)^{1/2}$$

with M_{Z_1} and M_{Z_2} being the masses for mass eigenstates Z_1 and Z_2, respectively.

In this letter, we study a possible extra Z_2 state and its interpretations which have direct implications for NP at LHC. Our interest is in Z_2 production and possible pair production process $Z_2(W,Z)$ with Z_2 decay into pairs of heavy quarks leading to $\bar{Q}Q$ and $\bar{Q}Q(W,Z)$ events at LHC with $\bar{Q}Q$ invariant mass peaked at the mass up to an order of O(0.4 TeV). If the Z_2 state is heavy enough to produce the H boson, one can determine the effective coupling of the Z_2-H interaction. We are to give the estimation of the partial decay widths Γ ratio

$$R(Z_2 \to H\{\bar{Q}Q\}_{s=1}/\bar{Q}Q) \equiv \frac{\Gamma(Z_2 \to H\{\bar{Q}Q\}_{s=1})}{\Gamma(Z_2 \to \bar{Q}Q)} \ , \tag{1}$$

where $\{\bar{Q}Q\}_{s=1}$ stands for a spin-1 quark-antiquark bound state.

2. To analyze the Z_2 state effects within the model under consideration, let us concentrate on the Z_2 couplings. Neglecting the interactions of Z bosons to leptons ("leptophobic" character of Z bosons) the interactions of mass eigenstates Z_i $(i > 1)$ with heavy quarks are described by the following Lagrangian density:

$$- L_{Z_i Q} = g_Z \sum_{i=1}^{\infty} \sum_{Q} \bar{Q}(g_{V_i} - g_{A_i}\gamma_5)\gamma^{\mu} Q Z_{i_\mu} \ , \tag{2}$$

where one of the sums runs over all heavy quarks Q, g_Z is presented as the SM coupling $g/\sqrt{1-s_W^2}$ $(s_W \equiv \sin\Theta_W)$, Z_{1_μ} is understood as the SM Z boson field while Z_j with $j \geq 2$ are additional Z states in the weak-eigenstate basis. We shall consider the model with one light Z_2 mass eigenstate only. The vector g_{V_i} and the axial g_{A_i} couplings (i=1,2) in (2) are defined as

$$g_{V_1} = g_V \cos\kappa + g'_V \alpha \sin\kappa \ \ , g_{A_1} = g_A \cos\kappa + g'_A \alpha \sin\kappa \ , \tag{3}$$

$$g_{V_2} = \alpha g'_V \cos\kappa - g_V \sin\kappa \ \ , g_{A_2} = \alpha g'_A \cos\kappa - g_A \sin\kappa \tag{4}$$

with

$$g_V = \frac{1}{2}T_{3L} - s_W^2 \cdot e_Q \ , \ g_A = \frac{1}{2}T_{3L} \ ,$$

for T_{3L} and e_Q being the third component of the weak isospin and the electric charge, respectively. Both g'_V and g'_A in (3)-(4) represent the chiral properties

of the Z' boson interplay with quarks and the relative strengths of these interactions

$$-L_{Z'Q} = g'_Z \sum_Q \bar{Q}(g'_V - g'_A\gamma_5)\gamma^\mu Q Z'_\mu \ . \tag{5}$$

For the GUT models, the free parameter g'_Z in (5) is related to α in (3)-(4) as $\alpha \equiv (g'_Z/g_Z) = \sqrt{(5/3)\omega}\cdot s_W$ [4], where ω depends on the symmetry breaking pattern and the fermion sector of the model, but is usually taken $\omega \sim 2/3$-1. The choice of $\alpha \simeq 0.62$ provides the equality of both g_Z and g'_Z on the scale of the mass of the unification $M_X \simeq M_{GUT}$ into E_6. Neglecting some differences in the renormalization group evolution of both g_Z and g'_Z, one can deal with α at the energies $\sim M_{Z'} \sim M_{Z_2} \sim$ O(1 TeV).

Suppose that the Z_2 state could be produced at LHC via $\bar{Q}Q \to Z_2$ subprocess, and in the narrow Z_2 width approximation the cross section

$$\sigma(\bar{Q}Q \to Z_2) = K(M_{Z_2})\frac{2\pi G_F M^2_{Z_1}}{3\sqrt{2}}(g^2_{V_2} + g^2_{A_2})\delta(s - M_{Z_2})$$

is both M_{Z_2}- and κ- dependent. Here, G_F is the Fermi constant and K factor reflects the higher order QCD process [5]

$$K(M_{Z_2}) = 1 + \frac{\alpha_s(M^2_{Z_2})}{2\ \pi}\frac{4}{3}\left(1 + \frac{4}{3}\ \pi^2\right) \ .$$

Note that two-loop $\alpha_s(M^2_{Z_2})$ ~0.1 for Λ_{QCD}= 200 MeV at $M_{Z_2} < 2m_t$ (5 flavors) and $M_{Z_2} > 2m_t$ (6 flavors) for m_t being the top quark mass [2].

The partial width for Z_2 decays into quarks is determined by the couplings g_{V_2} and g_{A_2} (4), namely (the number of colors N_c=3 is taken into account)

$$\Gamma(Z_2 \to \bar{Q}Q) = \frac{2\ G_F\ M^2_Z}{\sqrt{2}\ \pi}\ C(M^2_{Z_2})\ M_{Z_2}$$
$$\times(1 - 4r_q)^{1/2}\left[g^2_{V_2}(1 + 2r_q) + g^2_{A_2}(1 - 4r_q)\right]. \tag{6}$$

Here, $r_q \equiv m^2/M^2_{Z_2}$, M_Z and m are the masses of the Z boson and a quark, respectively, while the C factor is defined by the running strong coupling constant α_s

$$C(\mu^2) = 1 + \frac{\alpha_s(\mu^2)}{\pi} + 1.409\frac{\alpha^2_s(\mu^2)}{\pi^2} - 12.77\frac{\alpha^3_s(\mu^2)}{\pi^3}$$

with an arbitrary scale μ. The interactions of the Z_2 state with quarks are expressed in terms of three parameters x, y^u and y^d [1], where labels u and d mean the up- and down-type of quarks

$$2g^u_{V_2} = x + y^u \quad , -2g^u_{A_2} = -x + y^u \quad ,$$

$$2g^d_{V_2} = x + y^d \quad , -2g^d_{A_2} = -x + y^d \quad ,$$

3. The $\{\bar{Q}Q\}_{s=1}$ bound state with the 4-momentum Q_μ and the mass m_B may be produced in the Z_2 state decay via the H boson emission with the 4-momentum k_μ in a heavy quark-loop scheme. The decay amplitude is written as

$$A(k,Q) = \int d_4q \; Tr \left\{ \Gamma^+_Q(q) \cdot \sum_{i=1}^{3} T_i(q,k;Q) \right\} \;, \tag{7}$$

where $\Gamma_Q(q_\mu)$ is the spin-1 quark bound state vertex function depending on the relative momentum q_μ of $\bar{Q}$ and Q, while T_i are the rest of the total matrix element. In fact, T_i in (7) carry the dependence of interplay of H to heavy quarks (i=1,2) and Z_2 state to H boson (i=3) via the couplings $g_H = m/\langle H\rangle_0$ and $g_{Z_2H} = 2M^2_{Z_2}/\langle H\rangle_0$, respectively, where $\langle H\rangle_0$ stands for the vacuum expectation value of the singlet field H. Generally, $\Gamma_Q(q_\mu)$ is constructed [6] in terms of quark $u(Q_\mu)$ and antiquark $v(\bar{Q}_\mu)$ spinors in a given spin configuration accompanied by the covariant confinement-type wave function $\phi_Q(q^2;\beta)$ (in $\Re(S_4)$) containing the model parameter β [7]

$$\Gamma_Q(q_\mu) = \bar{u}(Q_\mu)\frac{\delta^j_i}{\sqrt{3}} \; U_{\alpha\beta} \; \phi_Q(q^2;\beta) \; v(\bar{Q}_\mu) \;. \tag{8}$$

Here, the second rank symmetric spinors $U_{\alpha\beta}$ obey the standard Bargman-Wigner equations [8] $(\not{Q} - m_B)^{\alpha'}_{\alpha} U_{\alpha'\beta} = 0$.

The decay width of $Z_2 \to H\{\bar{Q}Q\}_{s=1}$ is given by

$$\Gamma(Z_2 \to H\{\bar{Q}Q\}_{s=1}) = \frac{g^2_Z g^2_{V_2} M^3_{Z_2} N_C \cos^2\vartheta x^2_\beta \sqrt{\lambda(1,x_H,x_B)}}{\pi^3(1-x_B)\langle H\rangle^2_0}$$

$$\cdot(1-6x_\beta/x_B) \times \left\{ \frac{1}{4d_0}\left[\frac{1}{3}(1-x_H)\left(1-5\frac{x_\beta}{d_0}\right) + \frac{5}{12}x_B\left(1+\frac{8x_\beta}{5d_0}\right) + \frac{1}{4}x_B \right.\right.$$

$$\left.\left. -5x_\beta - \frac{1}{3}(x_H - x_B)^2\left(1+4\frac{x_\beta}{d_0}\right)\right] + \frac{1-6x_\beta/x_B}{1-x_B}\right\}, \tag{9}$$

where $r_B \simeq (2m/M_{Z_2})^2$, $x_H \equiv (m_H/M_{Z_2})^2$ $x_\beta \equiv \beta/M^2_{Z_2}$, $d_0 \simeq \frac{1}{2}(1+x_H-x_B)$, $\cos\vartheta \equiv (\epsilon\cdot\epsilon_{Z_2})$ for ϵ^μ and $\epsilon^\mu_{Z_2}$ being the polarization four-vectors of B and Z_2 state, respectively.
The total relative width $R(Z_2 \to H\{\bar{b}b\}_{s=1}/\bar{b}b)$ (1), derived from Eqs. (6) and (9) in the case when B is composed of $\bar{b}b$ but for the $\bar{b}b$ DY-type normalization, is presented in Table 1 as a function of the H boson mass m_H via the ratio x_H.

<u>*Table1*</u> The values of $R(Z_2 \to H\{\bar{b}b\}_{s=1}/\bar{b}b) \times 10^{10}$ for various embedding scales M_{Z_2} and Higgs boson masses m_H via the ratio $x_H = (m_H/M_{Z_2})^2$.

	x_H					
M_{Z_2} (TeV)	0	0.2	0.4	0.6	0.8	0.9
0.2	2.60	2.00	1.40	0.90	0.43	0.21
0.3	1.20	0.90	0.62	0.40	0.19	0.09
0.5	0.42	0.32	0.23	0.15	0.07	0.03
0.7	0.21	0.16	0.11	0.07	0.04	0.02

To be definite we have considered four values of M_{Z_2}=0.2, 0.3, 0.5 and 0.7 TeV. As can be seen, the distribution is very steeply peaked towards low H boson masses and drops to zero at high mass end. In fact, the results are valid for any masses by simply rescaling the ratios $x_{H,B,\beta}$. To be understood precisely, one has to note the following: firstly, the B state is treated relativistically (see (8)) and in the zero binding energy $m_B \simeq$ 2m; secondly, gluon corrections to the process have not been included. For a heavy B state such as $\{\bar{b}b\}_{s=1}$ or $\{\bar{t}t\}_{s=1}$, both of these approximations should be accepted. For a light spin-1 B state (heavier Higgs boson), the results can only be taken as a guide of an order of magnitude of the rates.

The only interesting point has been omitted from our consideration, namely, the Z'-decays via spin-1/2 exotic quarks (h) with Higgs boson emission. The exotic quarkonium $\{\bar{h}h\}$ and open flavor $\{\bar{Q}h\}$ bound states of the exotic h-quark production are under consideration, while they have gained attention in many papers. These bound states, eg., $\{\bar{h}Q\}$, can be formed since the spectator decays of a heavy quark constituent $h \to Q + H$ or $h \to Q + W(Z)$ are expected to be suppressed due to small mixing of exotic-SM constituents. The model presented in this letter is an instructive one to study and discover extra gauge bosons at LHC and NLC .

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